13th International Brick and
Block Masonry Conference
Amsterdam, July 4-7, 2004

BOND STRENGTH OF CLAY MASONRY PRISMS CONSTRUCTED WITH NORMAL AND FLY ASH SUBSTITUTED MORTARS

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Abstract

The interface between mortar and brick unit has been shown to have a high concentration of lime. Pozzolans such as fly ash, react with lime to produce calcium silicate hydrate gel – much stronger than lime. The reaction speed is slow, so any gain in strength will take a long time to develop. The spherical shape and size of fly ash particles causes fly ash to improve workability and water retentivity. We replaced some of the cementitious materials in both Portland cement-lime and masonry cement mortars with fly ash. Prisms were constructed with different units and mortars. Bond strength gain under moist and dry curing conditions was assessed at 28 and 360 days of age. We conclude that replacement of some cementitious materials with fly ash can result in satisfactory bond strength with a variety of units.

Key Words

Masonry bond, masonry mortar, fly ash and bond strength.

1 Introduction

For many years masonry has been known as a material with weak bond strength. Low bond strength affects serviceability and durability adversely. In spite of the research carried out over the last 70 years (e.g. Palmer and Parsons 1934, Kampf 1963, Grandet 1973, Chase 1984, Sugo et al. 1997, Groot 1997, Lange et al. 1999 and Sugo et al. 2001) on understanding and enhancing masonry bond, cracks similar to those in Figure 1 in a masonry wall from shear loading are very common. With no changes in materials, such cracks will continue to occur. We have investigated if it is possible to enhance masonry bond by incorporating pozzolanic materials, especially fly ash, into masonry mortars.

Previous research on masonry bond has shown that two bond mechanisms interact to develop bond strength: chemical bonding, where covalent or Van der Waals bonds

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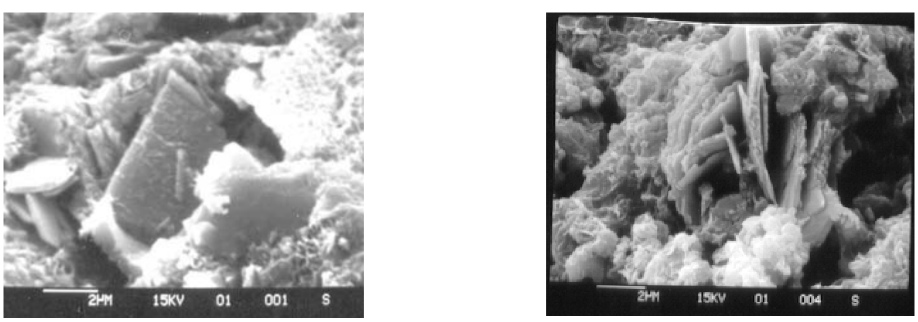
constitute the bond strength between the brick unit and the cement hydrates; and mechanical bonding formed by mechanical interlocking of hydration products transferred into the surface pores of the unit. It has been argued that the mechanical bond is much stronger than the chemical one (Dubovoy and Ribar 1990).

Figure 1 A typical shear crack at the weak masonry interface (Courtesy of S. L. Lissel)

Pozzolanic materials (e.g. fly ash and slag) are waste industrial materials which are usually cheaper than Portland cement. North American standards (CSA A23.5M-86, 1986 and ASTM 618-95, 1995) recognize two types of fly ash: class C originating from subbituminous coal origin and class F from bituminous coal. The main difference between these classes is that class C has higher calcium content than class F. Both fly ash and slag have been reported to enhance the properties of fresh and hardened concrete increasing long-term strength and durability (Aïtcin 1998). The effects have been attributed to pozzolanic activity, the chemical conversion of the weak CH crystals to strong CSH fibrous gel at a rate which depends on the chemical composition and fineness of the pozzolans. However, the effect of pozzolans on the bond and bond strength of masonry has only been investigated recently (Reda and Shrive 2000).The rate of reaction is slow, so the characteristic 28-day mortar strength will not necessarily reflect the long-term behaviour of fly ash mortar.

2 Microstructure of masonry interface

There have been differing observations regarding the existence and role of CH crystals at the mortar-unit interface. Lange et al. (1999) observed very few CH crystals at the interface and reported the contribution of CH to bond strength to be non-significant. However, Reda and Shrive (2000) and Sugo et al. (2001) have shown with SEM investigations and XRDA analysis that there are numerous CH crystals at the interface, as seen in Figure 2.



[a] [b]

Figure 2 CH crystals in the masonry interface (Courtesy of M. M. Reda Taha)

3 Experimental programme

A preliminary investigation (Reda and Shrive 2000) showed that replacing lime by fly ash in the range of 15 to 20% resulted in a significant enhancement in bond strength. Therefore, an extended experimental programme examining the effect of pozzolanic materials on the bond strength of masonry has been executed. The programme examined different types of mortars, brick units and curing regimes. The programme consisted of two consecutive phases. Different types of pozzolans were examined in phase 1, while in phase 2 the investigation included examining the effects of different mortar types with and without fly ash, the type of brick unit, and the curing regime on the bond strength of masonry. Some of the results are presented here.

3.1 Phase 1

3.1.1 Material

The materials used included two types of cement: Ordinary Portland cement and slag blended cement complying with the Canadian specifications for blended cements (CAN-A362, 1998). The hydrated lime was in conformance with ASTM C821-78 (1984). Two types of fly ash were also incorporated; class F and class C complying with ASTM C 618-95 (1995). All specimens were built using extruded clay bricks 90 mm x 190 mm each. The means of the basic properties of these brick units (ASTM C67-86, 1986) are given in Table 1.

Table 1 Properties of the brick units used in Phase I

Group designation	Colour	Compressive strength (MPa)	IRA (kg/m^2/minute)	Total Absorption %	Sorptivity index
A	Dark natural	47.3	2.2	7.6	N/A

Table 2 Mix proportions for four types of mortar with different types of pozzolans

Mortar group	Portland Cement	Slag Cement	Hydrated lime	Fly ash Type (F)	Fly ash Type (C)	Sand
I	1	---	1	---	---	6
II	0.8	---	0.8	---	0.4	6
III	0.8	---	0.8	0.4	---	6
IV	---	1	1	---	---	6

The pozzolans were used as partial replacement of either the cement or the cement and the lime in Type N mortar (CSA A179-94, 1994). The four mortars examined are presented in Table 2. The level of pozzolan replacement was based on the effect of class F fly ash (Reda and Shrive 2000). To examine the effect of slag cement; Type 10 Portland cement was replaced by slag-cement. No replacement of lime was incorporated in this mix. Fifteen five-high stack bonded prisms were made with each mortar type. All prisms were moist cured a fog room at 20 ^oC and 100 percent relative humidity. Masonry prisms were tested at 28 days, 90 days and 180 days of age.

3.1.2 Bond Testing

The bond wrench test apparatus used here is described in Shrive and Tilleman (1992). The top half of the brick is gripped between two neoprene pads in a clamp and a torque wrench is then attached to the clamp such that the centre-line of the torque wrench arm is centred on the brick.

3.1.3 Test results, Phase 1

All mortars incorporating fly ash showed consistent and acceptable workability with a pot life in excess of two and half hours. The values of interface bond strength of the

five prisms tested at each of the three ages (28, 90 and 180 days) for the four different types of mortar are presented in Table 3. Each value in the table represents the mean of the four mortar layers from each of the five masonry prisms (n=20).

Table 3 Test results of masonry bond strength (MPa)

	I	II	III	IV
Age		28 days		
Mean	0.72	0.54	0.81	0.42
Standard Deviation	0.14	0.05	0.05	0.06
Age		90 days		
Mean	0.74	0.72	1.06	0.52
Standard Deviation	0.09	0.12	0.11	0.11
Age		180 days		
Mean	0.79	0.88	1.14	0.56
Standard Deviation	0.15	0.06	0.12	0.09

The results show an increase in bond strength with age when either class C (group II) or class F fly ash (group III) was incorporated in the masonry mortar and lower bond strength at all ages when the Portland cement was replaced by slag cement (group IV). Comparing group II mortar (including class C fly ash) with Type N mortar (group I), the bond strength of group II mortar was 25 percent lower at 28 days, approximately equal at 90 days and then 11 percent higher than with the Type N mortar at 180 days. The bond strength of group III mortar (including class F fly ash) was consistently higher than that of Type N mortar by 12, 43 and 44 percent at 28, 90 and 180 days respectively. Mortar including slag cement (group IV) showed bond strengths lower than Type N mortar by 42, 30 and 29 percent respectively.
Statistical analyses using analysis of variance (ANOVA) assuming a 5 percent level of significance were performed to examine the significance of incorporating the different types of pozzolans in the masonry mortar on the mortar-unit interface bond strength. The statistical analysis showed that partial substitution of the cementitious materials with fly ash can result in a significant increase in the bond strength with the type of brick unit used in this test series. Further statistical analysis using the student t-test showed that replacing part of the Portland cement and lime by class F fly ash significantly improved the bond strength of the masonry at later testing ages - older than 90 days - with moist curing conditions. However, neither class C fly ash nor the cement slag resulted in significant enhancement in masonry bond strength.

3.2 Phase 2

3.2.1 Material

Based on results of phase 1, a second set of experiments was performed to examine the effect of changing the type of brick unit with three types of mortar – a Type N Portland cement-lime (mix V), a Type N masonry cement (mix VI) and a Type N mortar with 20 % replacement of the Portland cement and lime by fly ash (mix VII).

Table 4 Mix proportions by volume for the three masonry mortar used in Phase 2

Mortar group number	Portland Cement	Masonry Cement	Hydrated lime	Fly ash Type (F)	Sand
V	1	---	1	---	6
VI	---	1	---	---	3
VII	0.8	---	0.8	0.4	6

The flexural bond strength tests were performed after 28 and 360 days of curing under moist and dry conditions. The designation of the brick types and their properties

including the compressive strength, the initial rate of absorption, the sorptivity index and the total absorption are shown in Table 5.

Table 5 Properties of the brick units used in Stage II

Group designation	Colour	Compressive strength (MPa)	IRA (kg/m^2/minute)	Total Absorption %	Sorptivity index
B	Dark orange	44	7.1	8.1	2347
C	Light orange	39	12.7	8.0	5781
D	Natural	59	4.7	8.3	1465

A description of the sorptivity index and its ability to describe water absorption criteria in brick units is provided elsewhere (Reda Taha et al. 2001). The mean values of the interface bond strength of the four mortar layers in each of the four masonry prisms (n=16) tested at two ages (28 and 360 days) for the three different types of mortar are presented in Table 6. The results show a high dependency of the masonry bond strength on the brick type and also that curing has a significant effect on bond strength development with and without fly ash. There is a consistent increase in masonry bond strength with all types of mortars and brick units when moist curing is used. The bond strength increase was either much smaller or non-existent when the masonry prisms were left to cure under dry conditions.

*Table 6 Test results of masonry bond strength (MPa)**

Mortar Mix	Age (days)	Brick type					
		B		C		D	
		Moist	Dry	Moist	Dry	Moist	Dry
V	28 days	0.67 (±0.11)	0.86 (±0.21)	0.43 (±0.06)	0.43 (±0.11)	0.39 (±0.09)	0.34 (±0.07)
	360 days	1.2 (±0.05)	0.95 (±0.12)	1.01 (±0.10)	0.55 (±0.09)	0.78 (±0.08)	0.38 (±0.07)
VI	28 days	0.34 (±0.11)	0.33 (±0.24)	0.28 (±0.10)	0.08 (±0.03)	0.32 (±0.07)	0.31 (±0.08)
	360 days	0.71 (±0.08)	0.26 (±0.11)	0.76 (±0.15)	0.18 (±0.05)	0.74 (±0.08)	0.35 (±0.05)
VII	28 days	0.48 (±0.07)	0.59 (±0.10)	0.34 (±0.03)	0.26 (±0.03)	0.38 (±0.04)	0.32 (±0.04)
	360 days	0.88 (±0.07)	0.67 (±0.07)	0.53 (±0.08)	0.36 (±0.06)	0.61 (±0.05)	0.47 (±0.07)

- values in brackets representing standard deviations

Brick types B and C had higher bond strength than obtained with type D brick units. All three brick types have similar total absorption, suggesting that absorption is not a sensitive measure for predicting bond strength. The bond strength development of type D bricks when used with Type N Portland cement-lime mortar (mix V) was close to that of the Type A bricks with the same mortar during phase 1 of this programme. However, the bond strength between fly ash mortar and type D brick units was lower at 360 days than when the same mortar was used with type A brick units.

4 Discussion

The large number of parameters involved in the experimental investigation analysis makes it difficult to observe a specific trend for changes in bond strength. Therefore, statistical analysis using ANOVA was performed to examine the significance of incorporating the different types of mortars, different types of brick units as well as different curing regimes.

4.1 The significance of mortar types on bond strength

ANOVA was performed first to examine the significance of changing the mortar type on bond strength. Further statistical analysis using the student t-test examined the existence of significant differences between pairs of samples with different mortar types. Comparisons were only made between moist cured masonry prisms at 360 days of age. The results of the t-student test between different pairs of the masonry mortar types are presented in Table 7.

The statistical analysis showed that replacing part of the Portland cement and lime by class F fly ash reduces the bond strength with all three brick units (B, C and D) significantly when moist cured to 360 days of age, compared to Type N mortar. This is in contrast to the increase in bond strength observed with type A brick units in phase 1. However, when type B brick units were used with fly ash substituted mortar (mix VII) a significant increase in bond strength (24%) occurred compared to masonry cement Type N mortar (mix VI). With dry curing, different results occur.

*Table 7 The significance of changing mortar type on bond strength: moist curing**

Compared mortars	Brick unit Type		
	B	C	D
V-VI	SD	SD	ND
VI-VII	SD	SD	SD
V-VII	SD	SD	SD

- SD indicates significantly different, ND indicates non different

4.2 The significance of brick units on bond strength

ANOVA was also performed to examine the significance of changing the brick units on bond strength. The analysis also includes the use of the student t-test to examine the significance of the difference between pairs of samples with different brick units. Again, comparisons were only made between moist cured masonry prisms at 360 days of age. The results of the t-student test between pairs of brick units are presented in Table 8.

*Table 8 The significance of changing brick unit type on bond strength**

Compared mortars	Brick unit Type		
	V	VI	VII
B-C	SD	ND	SD
B-D	SD	ND	SD
C-D	SD	ND	SD

- SD indicates significantly different, ND indicates non different

The analysis showed that masonry cement mortar (mix VI) is the only type of mortar that was unaffected when the brick units were changed. This means that this type of mortar governs the bond strength of the masonry interface. In contrast, both Type N (group V) and fly ash substituted mortar (mix VII) showed considerable sensitivity to changes in the brick type. The sensitivity of the fly ash mortar is also confirmed with the inability of the fly ash mortars tested in phase 2 to reach bond strength levels similar to those achieved in phase I with different types of brick. We note that the type A units have a lower IRA than the brick units used in phase 2.

*Table 9 Significance between brick unit properties for units used in phases 1 and 2**

Compared property	Level of difference
Compressive strength	SD
Total absorption	SD
IRA	SD
Sorptivity	SD

- SD indicates significantly different, ND indicates non different

Statistical analysis also showed the existence of a significant difference between the different types of brick units (A, B, C and D). The biggest difference between these units in the properties measured is in the water absorption criteria (IRA and Sorptivity) and thus it appears that these properties are of importance in the development of bond strength between these brick units and mortars.

4.3 The significance of curing on bond strength

Finally, statistical analysis to examine the significance of changing the curing regime on bond strength was performed. The significance of the difference between pairs of samples with moist and dry curing for the three mortar mixes V, VI and VII was performed using the student t-test. Comparisons were again made at 360 days of age only. The results of the t-student test between pairs of brick units are presented in Table 10. The analysis showed that curing had a significant effect on bond strength development, as has been shown before (e.g.: Reda and Shrive 2000).

*Table 10 The significance of curing regime on bond strength**

Compared mortars	Brick unit Type		
	V	VI	VII
Moist curing vs. dry curing (Brick unit B)	SD	SD	SD
Moist curing vs. dry curing (Brick unit C)	SD	SD	SD
Moist curing vs. dry curing (Brick unit D)	SD	SD	SD

• SD indicates significantly different, ND indicates non different

4.4 Overall analysis

The increased number of parameters in the investigation shows that fly ash substitution can be used with some types of brick units to provide satisfactory flexural bond strength. However, fly ash substitution is not always beneficial. Nevertheless, even in the cases where fly ash did not achieve bond strengths similar to that of Type N mortar, bond strengths were never less than the minimum required by most standards (0.2 MPa) (CSA A179–94, 1994). The contribution of the fly ash in developing interface masonry bond can not attributed solely to the pozzolanic activity of the pozzolans (i.e. converting the weak CH crystals to a strong CSH fibrous network). Other factors related to mortar water retention/brick unit suction and the size of the pozzolan particles and their capability to reduce the wall effect also have significant influence in determining the interface bond strength.

5 Conclusions

Fly ash can be used to substitute part of the cementitious materials in masonry mortar to improve long-term bond strength. However, the decision to use fly ash in masonry mortar should be based on bond strength, not compressive strength testing. The effect of pozzolans on masonry bond strength could not be attributed to the pozzolanic reaction alone. Other factors, both in the masonry mortar and those related to the water absorption criteria of the brick unit also have significant effect. While the reactivity of the pozzolanic material is needed for developing a strong CSH network, the effect of the other factors can adversely affect or completely stop this process. Thus, optimizing masonry bond strength is a process that requires examination of different combinations of mortars and brick units.

6 Acknowledgement

This work is supported by the Natural Sciences and Engineering Research Council of Canada (NSERC), I-XL Industries and the Masonry Contractors of Southern Alberta. The authors gratefully acknowledge this support.

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